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AN INVESTIGATION OF APOLLO LAUNCH ESCAPE VEHICLE WARNING TIME AND SEPARATION DISTANCE REQUIREMENTS DUE TO BLAST FOR AN ABORT FROM A THRUSTING C-1 LAUNCH VEHICLE (U)

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
Houston, Texas

May 8, 1964 [redacted]

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NASA PROGRAM APOLLO WORKING PAPER NO. 1122

AN INVESTIGATION OF APOLLO LAUNCH ESCAPE VEHICLE WARNING TIME AND SEPARATION DISTANCE REQUIREMENTS DUE TO BLAST FOR AN ABORT FROM A THRUSTING C-1 BOOSTER (U)

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AN INVESTIGATION OF APOLLO LAUNCH ESCAPE VEHICLE WARNING TIME AND SEPARATION DISTANCE REQUIREMENTS DUE TO BLAST FOR AN ABORT FROM A THRUSTING C-1 BOOSTER (U)

SUMMARY

In the event of a launch vehicle explosion, it will be necessary to abort the spacecraft prior to the explosion. The spacecraft must have sufficient warning of the impending explosion to achieve a safe separation distance. Otherwise, the spacecraft will suffer a structural failure due to excessive blast overpressures. This working paper gives the warning times necessary for the spacecraft to perform a successful abort from a Saturn C-1. It is restricted to explosions within the atmosphere, or more specifically at times prior to jettison of the Apollo launch escape system. Also included are the overpressures experienced by the Apollo spacecraft under various conditions.

The first part of the report is a general discussion of the various methods available for predicting blast overpressure, both on the ground and at altitude. Also included is a discussion of the trajectory analysis involved in computing separation distances for the launch escape vehicle from the launch vehicle. Finally, overpressures and warning times are calculated using the method described herein.

From this study it may be concluded that the maximum warning time necessary is in the flight region of maximum dynamic pressure and is less than five seconds.

INTRODUCTION

The safety of the crew in the event of a launch vehicle explosion is one of the considerations in the design of a manned spacecraft. The solution to this problem is not straightforward due to the many parameters which must be considered. This report attempts to analyze one facet of the problem, the determination of vehicle warning times necessary (due to blast overpressure) for a successful escape from a Saturn C-1 launch vehicle. No attempt has been made in this report to examine the effects of fragmentation or of fireballs. It is felt that the blast overpressures are the paramount problem.

The report is an attempt to show the entire procedure which was used in estimating blast effects within the atmosphere. The method may be applied equally well to any [redacted]

Similar work has been done in this area as indicated in the list of references. Also, as indicated by the references, considerable use has been made of the variable methods for predicting overpressures due to explosions.

SYMBOLS

a	Speed of sound, ft/sec
C_A	Aerodynamic axial force coefficient
C_{N_α}	Slope of aerodynamic normal force coefficient versus angle of attack curve, rad^{-1}
g	Acceleration due to gravity, ft/sec^2
I_z	Vehicle moment of inertia about the pitch axis, $slug\text{-}ft^2$
K	Factor to account for jet effects
M_o	Initial mass of the launch escape vehicle, slugs
M_T	Mass of launch escape vehicle at time = t, slugs
q	Dynamic pressure, psf
S_o	Aerodynamic reference area, ft^2
T_1	Launch escape motor thrust, lb
T_2	Pitch control motor thrust, lb
V_m	Vehicle velocity, ft/sec
X	Body fixed roll axis parallel to vehicle center line with origin at the center of gravity
X_{cg}	Distance along vehicle center line between the center of gravity and the heat shield substructure ablation material interface, ft

X_{cp} Distance along vehicle center line between the center of pressure and the heat shield substructure ablation material interface, ft

X_1 Distance along vehicle center line between the launch escape motor thrust origin and the heat shield substructure ablation material interface, ft

X_2 Distance along vehicle center line between the pitch control motor thrust origin and the heat shield substructure ablation material interface, ft

Y Body fixed yaw axis normal to roll axis with origin at the center of gravity

Y_{cg} Distance on yaw axis between center of gravity and vehicle center line, ft

c_p Pressure coefficient

h Altitude for initial abort conditions, ft

P_b Peak overpressure, atmospheres (relative to local ambient)

P_o Ambient pressure, psi

R Distance from center of explosion, ft

S_T Separation distance, ft

T_W Warning time, sec

T_o Initial time for abort from boost trajectory, sec

W Equivalent weight of propellants, lbs

ζ Propellant yield, percent of TNT

Z A parameter, $\frac{R}{W^{1/3}}$

E Blast energy, ft lb

[redacted]

E_{TNT}	Energy of TNT = $1.55 \times 10^6 \frac{\text{ft-lb}}{\text{lb TNT}}$
α_E	A parameter, $\left(\frac{E}{P_o}\right)^{1/3}$
M.N.	Mach number
Δh	Change in altitude after abort initiation, ft
ΔR	Change in range after abort initiation, ft
α	Angle of attack, degrees
γ	Flight path angle
ϵ	Angle at which launch escape motor thrust is canted relative to vehicle center line
θ	Vehicle pitch angle from the local vertical
$\bar{h}$	Angular momentum
$\bar{P}$	Linear momentum

MECHANISM OF A BLAST WAVE

The phenomena associated with the passage of a blast wave through the air will be qualitatively discussed here. In considering the destructive effect of a blast wave, one of the most important characteristics is the overpressure. The maximum value of the overpressure is called the peak overpressure and corresponds to the pressure at the shock wave. The sketch on the following page shows the shape of the blast overpressure curve as a function of time from detonation at some distance from the explosion.

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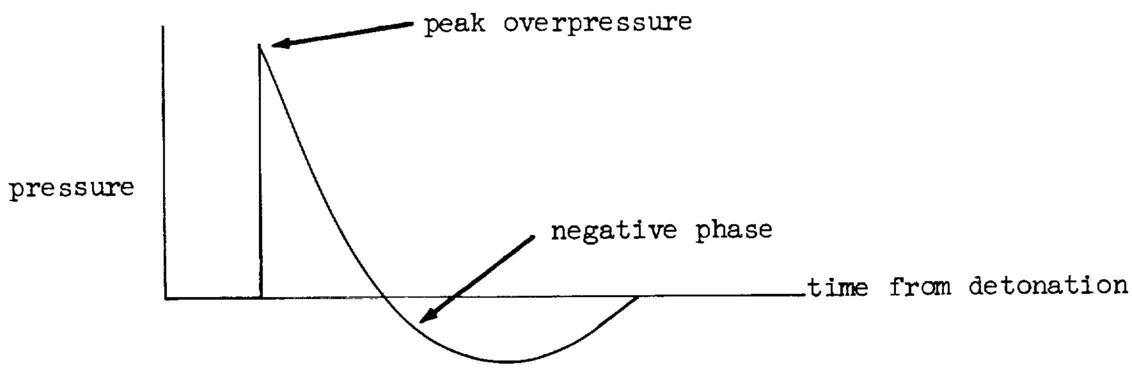


It is the peak overpressure which is of interest in this study.

The blast wave is generated when a region of very high pressures form as a result of the detonation. This pressure region expands rapidly as the shock front moves out, and the peak overpressure decreases as the energy of the explosion is expended in compressing progressively larger amounts of air.

The pressure behind the shock front decreases with distance behind the shock. This pressure decreases below that of the surrounding atmosphere, and the so-called "negative phase" of the blast wave forms. At the end of the negative phase, the pressure has essentially returned to ambient. The peak negative values of the overpressure are small compared with the peak positive overpressures and will not be considered in this analysis.

METHODS FOR OVERPRESSURE CALCULATIONS

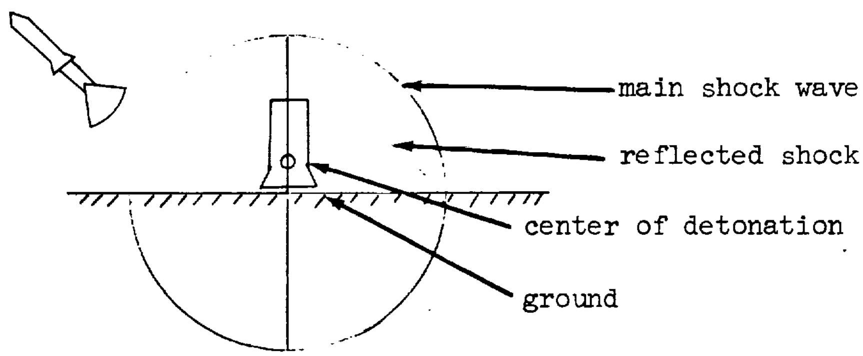
An investigation has been made of some of the methods available for the prediction of blast overpressures. Some of these methods are based entirely on empirical data while others are analytical. As would be expected, there is a great deal more information available for ground level explosions than for explosions at altitude. From the available methods, one was chosen which could be used for both ground and air explosions and which gave conservative answers when applied to the specific problem described herein. The overpressures calculated using these methods are the peak values as defined in the section on the mechanism of a blast wave.

[redacted]

GROUND LEVEL EXPLOSIONS

Figure 1 shows a comparison of the methods used to analyze a ground level explosion. Peak overpressure (P_b) is plotted as a function of distance from the center of the detonation. It should be noted that the curves have been plotted on semi-log graph paper which tends to show at first glance better agreement than actually exists.

It is convenient to mention at this time the reflected shock which occurs as a result of an explosion in the proximity of the ground. As indicated in the sketch, the blast wave strikes the ground and is reflected.



If it is assumed that a perfect reflection occurs, then the reflected shock will reinforce the main shock at some distance from the explosion. The reflected shock will, in general, eventually overtake the main shock because it travels through air that has been heated and compressed by the passage of the main shock wave.

In the calculation presented here, it is assumed that a ground level explosion of E ft-lbs of energy is equivalent in blast characteristics to an explosion of 2E ft-lbs high in the air. This would be true only if the ground were an absolutely rigid reflecting surface. Therefore, the 2E assumption is conservative to some extent. The 2 is referred to as the ground reflection factor.

The methods compared in figure 1 are for the specific case of a Saturn C-1 explosion at lift-off. The TNT equivalent energy values, as defined in the section on propellant explosive potential, used for this particular example are:

[redacted]

LOX/LH_2 = 60 percent

LOX/RP-1 = 10 percent for the first 500,000 lbs

= 20 percent for addition propellant over 500,000 lbs

Smalley's empirical method (ref. 1) is based on data obtained from missile explosions of various sizes up to approximately 250,000 lbs of propellant. The equation is:

$$P_b = \frac{3016}{Z^3} + \frac{221}{Z^2} + \frac{38.1}{Z}$$

where

$$Z = \frac{R}{W^{1/3}}$$

This equation is applicable to a surface explosion using a ground reflection factor of 2.0. It is good for overpressures greater than 1 psi.

A somewhat similar equation is that used by the Army Corps of Engineers (ref. 2 p. 11-A-59) in the design of blast resistant structures:

$$P_b = \frac{4120}{Z^3} - \frac{105}{Z^2} + \frac{39.5}{Z}$$

Agreement between this equation and Smalley's is good at higher values of P_b. For smaller values of P_b, agreement is not as good. Like Smalley's method the equation is a curve fit to experimental data. This equation, however, is based on explosive charges rather than missile fuel detonations.

A third method in widespread use is outlined in reference 3, "The Effects of Nuclear Weapons." The equations used in this analysis are derived from the Rankine-Hugoniot conditions based on the conservation of mass, energy, and momentum at the shock front. These conditions, together with the equation of state for air, permit the derivation of the required relations involving the shock velocity, the overpressure, the dynamic pressure, and the density of the air behind the ideal shock front. Application of the method is clearly outlined with examples in the reference.

Taylor's method (ref. 4) is likewise an analytical approach to the problem, having been derived for use in estimating the effects of atomic explosions. The analysis, according to the author, ceases to be accurate for overpressures less than about 10 atmospheres. Figure 1 seems to bear this out. Taylor's method reduces to the expression,

$$P_b = \frac{3340}{Z^3}$$

The similarity between this formula and those of references 1 and 2 is obvious.

The final method considered for ground level explosions is that of Brode (ref. 5). It is a numerical solution to the partial differential equations of hydrodynamic motion. The method appears to agree well with the other methods (Taylor excepted). It yields overpressures which are about 10 percent lower than predicted by Smalley from actual missile explosion data. A more complete discussion of Brode's method will follow.

EXPLOSIONS AT ALTITUDE

Three of the methods previously mentioned may be applied to explosions at altitudes within the atmosphere where there exists a medium for propagating the shock wave. A comparison of these methods is shown in figure 2. The effects of change in altitude have been included in all three methods. A glance at the figure shows at once serious disagreement between the methods.

From previous discussion Taylor's method can be eliminated for use in analyzing the problem of interest here since we are concerned about values of P_b much less than 10 atmospheres. The method of reference 3 may be regarded with suspicion since it appears to follow Taylor fairly closely at lower pressures where Taylor is invalid. Brode's solution, (ref. 5) however, seems to present some interesting possibilities. With the other two analytical methods eliminated, there remains only Brode's, which is conservative by comparison. His method also agrees well with the other methods for the fairly well defined case of ground level explosions. For these reasons, Brode's analysis will be used here for the blast overpressure calculations involved in defining warning times and separation distances for the Apollo launch escape vehicle.

ASSUMPTIONS

A considerable number of simplifying assumptions have been made in this report. A list of the more important ones follows. They are justified elsewhere in the discussion.

1. The only effect of the shock front is to increase the uniform pressure over the launch escape vehicle.

2. No multiple booster failures, occur, that is a control system failure is not coupled with a maximum explosive yield.

3. For a ground level explosion, the energy is equivalent to twice the blast energy of a similar explosion at altitude.

4. The thrusting launch vehicle follows a straight line trajectory after separation of the spacecraft.

5. The separation distance calculated is the distance from the command module to the center of the explosion.

6. Spacecraft external pressures due to escape rocket jet effects have been neglected.

7. There is no cabin pressurization system failure following the abort. This means that the limit external absolute pressure, which includes the blast overpressure, will be constant at a particular flight time.

8. The blast wave intercepts the vehicle symmetrically so as to impose a symmetric pressure distribution.

9. Both Saturn C-1 launch vehicle stages are assumed to explode simultaneously.

10. Pressure lag due to the rapid rate of change of altitude between cabin pressure and ambient is zero.

PROPELLANT EXPLOSIVE POTENTIAL

In the calculation of blast overpressures one of the important parameters is the explosive equivalent of the propellants. This problem has been the subject of considerable study, but a completely satisfactory solution has not yet been found.

However, it can be shown that the warning times necessary for aborting from an exploding launch vehicle are not affected to a large extent by fairly large changes in the explosive potential.

A term in widespread use for describing explosive potential is "yield". It is defined as the number of pounds of TNT equivalent to the total propellant weight on board. The energy of TNT is

$$1.55 \times 10^6 \frac{\text{ft-lb}}{\text{LB TNT}}.$$

The following table gives the values of yield used in this report for estimating warning times.

Propellant Yield

Condition	LOX/RP-1	LOX/LH_2
1	10 percent	60 percent
2	5 percent	20 percent

The values in condition 1 (ref. 2) are the recommended values for use in design. These values have been recommended by the joint Air Force-NASA Hazards Analysis Board. Condition 2 was chosen as being a possibly more realistic case.

Warning times and separation distances have been computed for both of these conditions to illustrate the effects of yield.

TRAJECTORY ANALYSIS AND SEPARATION DISTANCES

An analog computer program was prepared to simulate the launch escape vehicle trajectory after abort initiation. Initial conditions were provided for parameters along a normal SA-5 trajectory, (ref. 10), with an impending explosion as the only cause for abort. Combining the launch escape system trajectory with an approximation of a straight line launch vehicle trajectory after abort initiation made possible a calculation of separation distance as a function of time.

The time changing properties of the launch escape system play an important role in its behavior and were prepared from the latest available data as functions of time.

The initial weight, center of gravity, and pitch moment of inertia of the system were obtained from reference 7. To obtain time varying plots, the launch escape motor fuel was assumed to be evenly distributed along its container at all times and weight was dropped from it at several time intervals according to the latest mass flow curves available (ref. 8). The launch escape motor thrust curve was based on predictions included in reference 8. The thrust vector offset angle had not been determined at the time of the study and the thrust vector was assumed to pass through the initial position of the center of gravity. The pitch control motor was estimated to have an impulse of 1,550 lb-sec.

All aerodynamic coefficients were obtained from FS-2 Component Loads Model Tests conducted at NASA-Ames Research Center, reference 9. The tests were conducted exclusive of jet effects and a factor as a function of altitude was included in the equations to approximate the effects of the jet on the aerodynamic normal force and pitching moment. The aerodynamic axial force was assumed to be unaffected by the jet and was directed along the vehicle axis. The normal force coefficient was linearized with angle of attack and the slope plotted as a function of Mach number.

DERIVATION OF ANALOG EQUATIONS

The three degrees-of-freedom rigid body equations of motion prepared for the simulation utilized a body fixed axis system with its origin at the center of gravity of the system. The launch escape vehicle configuration, coordinate system, and external forces are shown in figure 3.

Force Summation

Newton's second law of motion states that the vector summation of external forces acting on a system of particles equals the vector time rate of change of linear momentum of the system.

Consider the preceeding mass, M, being acted upon the the external force F_{ext}.

At $t = t_1$, linear momentum, $\overline{P}_1 = \overline{MV}_1$

At $t = t_1 + \Delta t$, linear momentum, $\overline{P}_2 = M(\overline{V_1 + \Delta V})$

The net change in momentum in time Δt:

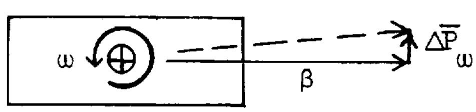
$$\overline{P}_2 - \overline{P}_1 = M(\overline{V_1 + \Delta V}) - \overline{MV}_1$$

$$\Delta\overline{P} = M\Delta\overline{V}$$

Divide by Δt and take $\lim_{\Delta t \to 0}$

$$\frac{d\overline{P}}{dt} = M\frac{d\overline{V}}{dt}$$

Assume now that the system of particles is also rotating about its center of gravity with an angular velocity, ω.



The linear momentum vector, $\overline{P}$, acquires in the time Δt, a change in the direction shown, of $\Delta\overline{P}_\omega = \Delta t\ (\overline{\omega} \times \overline{P})$. Thus the time rate of change of momentum due to rotation is $\overline{\omega} \times \overline{P}$.

Newton's second lay may now be stated:

$$1.\quad \Sigma\,\overline{F}_{ext} = \frac{d\overline{P}}{dt} + \overline{\omega} \times \overline{P} = M\,\frac{d\overline{V}}{dt} + \overline{\omega} \times \overline{P}$$

Applying this equation to the launch escape vehicle configuration:

$$\overline{V}_m = \dot{X}\,\overline{i} + \dot{Y}\,\overline{j}$$

$$\overline{\omega} = \dot{\theta}\,\overline{k}$$

$$\overline{P} = M\,\dot{X}\,\overline{i} + M\,\dot{Y}\,\overline{j}$$

$$\overline{\Sigma\ F_{ext}} = T_1 \cos \epsilon\ \overline{i} + T_1 \sin \epsilon\ \overline{j} - Mg \cos \theta\ \overline{i} + Mg \sin \theta\ \overline{j}$$

$$- C_A q\ S_o\ \overline{i} + K\ C_{N\alpha}\ \alpha q\ S_o\ \overline{j} + T_2\ \overline{j}$$

$$\left[T_1 \cos \epsilon - Mg \cos \theta - C_A\ q\ S_o\right] \overline{i} + \left[T_1 \sin \epsilon + Mg \sin \theta + K\ C_{N\alpha}\ \alpha q\ S_o + T_2\right] \overline{j} = M\,\ddot{X}\,\overline{i} + M\,\ddot{Y}\,\overline{j} + \dot{\theta}\overline{k} \times (M\,\dot{X}\,\overline{i} + M\,\dot{Y}\,\overline{j})$$

$$\ddot{X} = \dot{\theta}\dot{Y} - g \cos \theta - \frac{C_A q\ S_o}{M_T} + \frac{T_1 \cos \epsilon}{M_T} \tag{1a}$$

$$\ddot{Y} = - \dot{\theta}\dot{X} + g \sin \theta + \frac{K\ C_{N\alpha}\ \alpha q\ S_o}{M_T} + \frac{T_2}{M_T} + \frac{T_1 \sin \epsilon}{M_T} \tag{1b}$$

Moment Summation

The following relationship is used to establish the pitching moment equation. The moment about any line of the external system of forces acting on any body is equal to the rate at which the angular momentum of the body about that line is changing.

$\Sigma\ \overline{M_{ext}} = \frac{d\overline{h}}{dt}$, where $\overline{h}$ is the angular momentum vector.

The external moments considered are in the pitch plane and the line about which they act is the pitch axis through the center of gravity. The angular momentum of the vehicle about this axis is $\overline{I_z \omega_z}$.

[redacted]

Thus:

2. $$\Sigma \overline{M}_z = \frac{d}{dt}\left(\overline{I_z \omega_z}\right)$$

$$\overline{\omega}_z = \dot{\theta}\, \overline{k}$$

$$\Sigma \overline{M}_z = \left[T_2\left(X_2 - X_{cg}\right) - T_1 \cos\epsilon\, Y_{cg} + T_1 \sin\epsilon \left(X_1 - X_{cg}\right) + K\, C_{N\alpha}\, \alpha q\, S_o \left(X_{cp} - X_{cg}\right) + C_A q\, S_o\, Y_{cg}\right] \overline{k}$$

3. $$I_z\, \ddot{\theta} = T_2\left(X_2 - X_{cg}\right) - T_1 \cos\epsilon\, Y_{cg} + T_1 \sin\epsilon \left(X_1 - X_{cg}\right) + K\, C_{N\alpha}\, \alpha q\, S_o \left(X_{cp} - X_{cg}\right) + C_A q\, S_o\, Y_{cg}$$

Additional Equations

4. $$V^2_m = \dot{X}^2 + \dot{Y}^2$$

5. $$\alpha = \mathrm{TAN}^{-1}\left(-\frac{\dot{Y}}{\dot{X}}\right)$$

6. $$\Delta h = \int_o^t V_M \cos\gamma\, dt$$

7. $$\Delta R = \int_o^t V_M \sin\gamma\, dt$$

8. $$\gamma = \theta - \alpha$$

9. $$M_T = M_o + \int_o^t \dot{M}\, dt$$

10. $$M.N. = \frac{V_m}{a}$$

11. $$q = \frac{1}{2}\rho\, V_m^{\,2}$$

[redacted]

[redacted]

BOOSTER SIMULATION

Several assumptions were made to simplify the simulation of the booster trajectory for the first few seconds following abort. The booster was assumed to continue thrusting with an operative control system. It was also considered to have a constant acceleration equal to that of the system just prior to abort, and also to be traveling in a a straight line at its normal flight path angle for the short time under study.

Thus its distance along the path at time = t is:

$$S = \dot{X}t + \frac{1}{2}\ddot{X}t^2$$

Combining this launch vehicle trajectory with that calculated for the launch escape system made possible a determination of the separation distance at any time. Trajectories and separation distances are illustrated in figures 4 and 5.

METHOD FOR COMPUTING WARNING TIMES

In computing warning times, five different flight conditions have been considered. These conditions are tabulated below as obtained from reference 10.

Flight Conditions

T_o, sec	h, ft	q, psf	γ, deg	N.M.
0	0	0	0	0
50	19,000	555	19.8	.9
70	40,600	714	33.5	1.6
90	70,500	444	45.7	2.6
100	89,730	285	50.5	3.3

[redacted]

Propellant Remaining

T_o, sec	S-I propellant remaining, lbs	S-IV propellant remaining, lbs
0	879,600	98,000
50	584,400	
70	469,100	
90	351,800	
100	293,200	98,000

As previously mentioned, Brode's method has been used in the overpressure calculations. Figure 6 shows a curve of overpressure as a function of the parameter, R/α_E. This curve applies to a TNT explosion and is taken directly from reference 5. Once the yield and altitude are known, P_b may be obtained for any distance R from this curve. Figures 7 and 8 are plots of P_b versus R for the five flight times considered in this report.

From these curves of P_b versus S_t, figures 7 and 8, and from the curves of S_t versus time, figure 5, cross plots of P_b versus time may be obtained. Figures 9 and 10 show these values of overpressure versus warning time for the two yield conditions and five abort times.

With the warning time known as a function of blast overpressure, there remains only the problem of determining the allowable P_b during the flight.

It has previously been assumed that the blast wave will intercept the command module so as to impose a symmetric pressure distribution. It is also assumed that the net external pressure on the command module is the algebraic sum of the local pressure due to freestream dynamic pressure and the peak pressure due to the blast wave. Figure 11 shows the command module internal and external pressures as a function of time for lift-off during a nominal flight. All pressures shown are absolute. The limit allowable pressure due to a launch vehicle explosion is the difference between curves D and B. This difference is shown in figure 12.

The limit allowable differential pressure is based on early estimates of 12.67 psia between the cabin and outer shell. This estimate is for an external pressure distribution applied uniformly.

The warning times for the pressure in figure 12 are obtained from figures 9 and 10 and are plotted in figure 13 for the two yield conditions considered in this report. It may readily be seen that the maximum warning times are necessary at about 60 seconds flight time, which is in the transonic region just prior to maximum dynamic pressure.

CONCLUSIONS

The results of this study as summarized in figure 13 indicate the differences in warning time for the 2 yield conditions. It may be seen that large increases in explosive yield do not cause correspondingly large increases in the necessary warning time.

[redacted]

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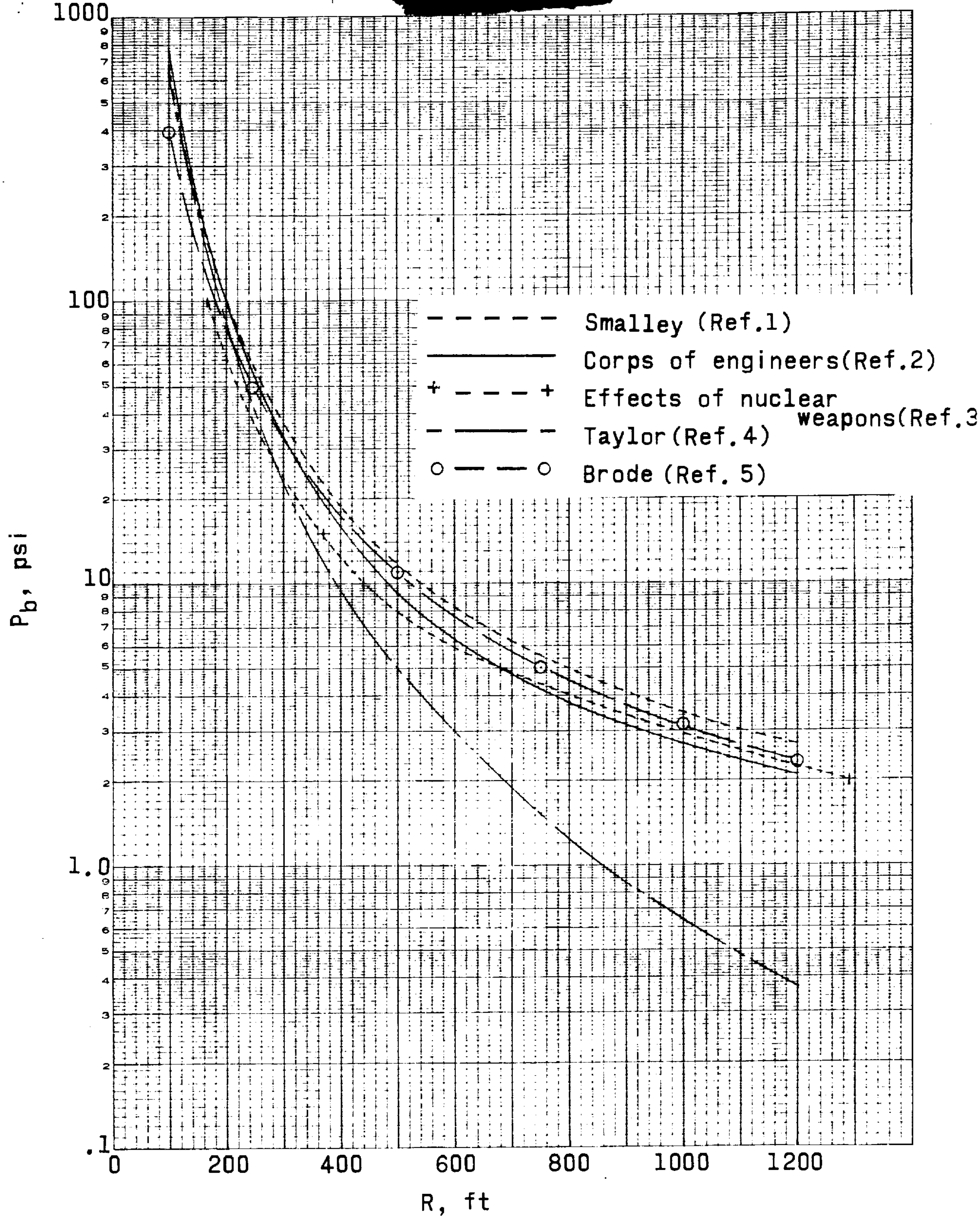

Figure 1.- Comparison of methods available for predicting overpressures (surface explosion).

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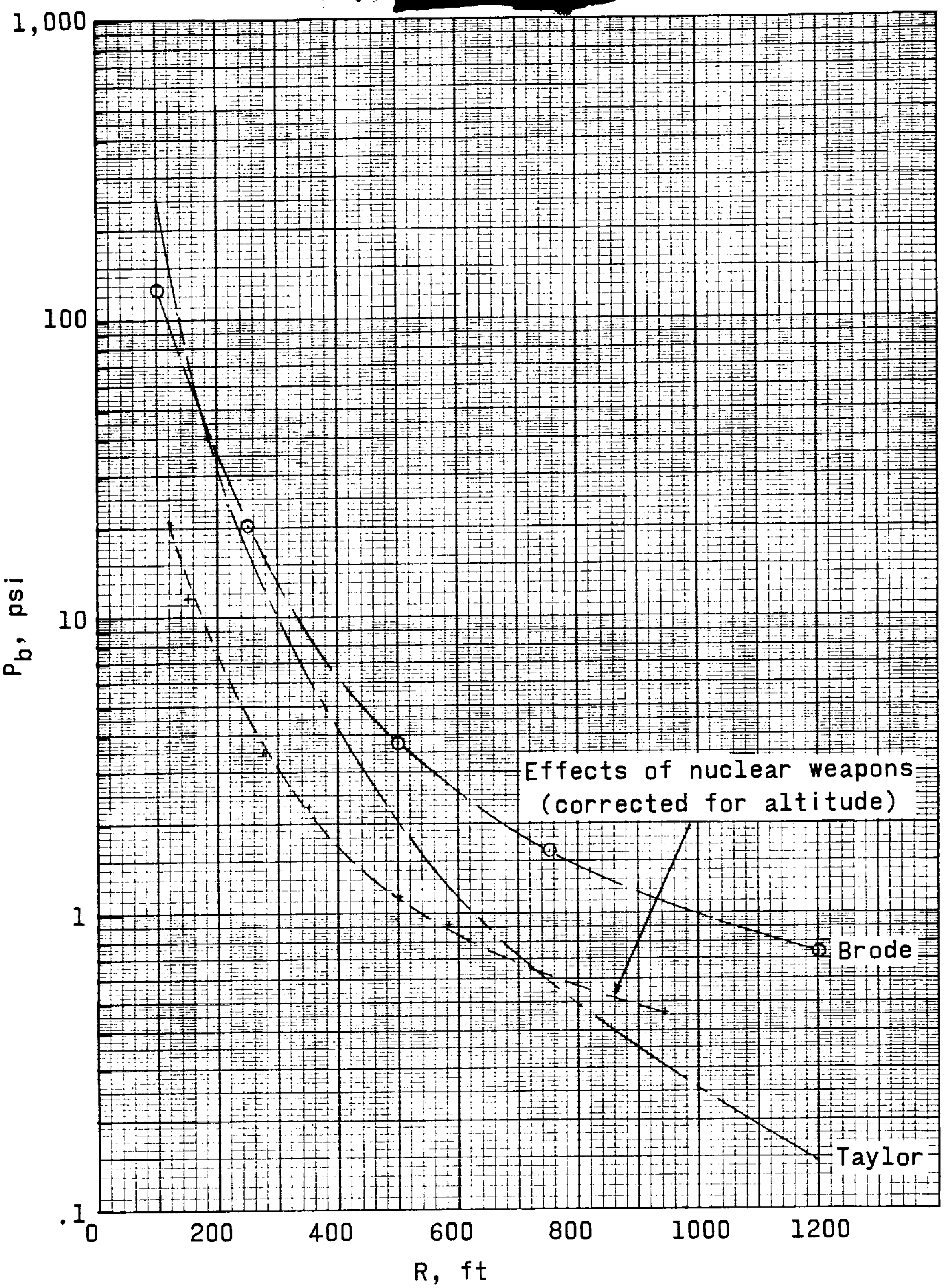

Figure 2.- Comparison of methods available for predicting overpressures (explosion at altitude, h = 36,700 feet).

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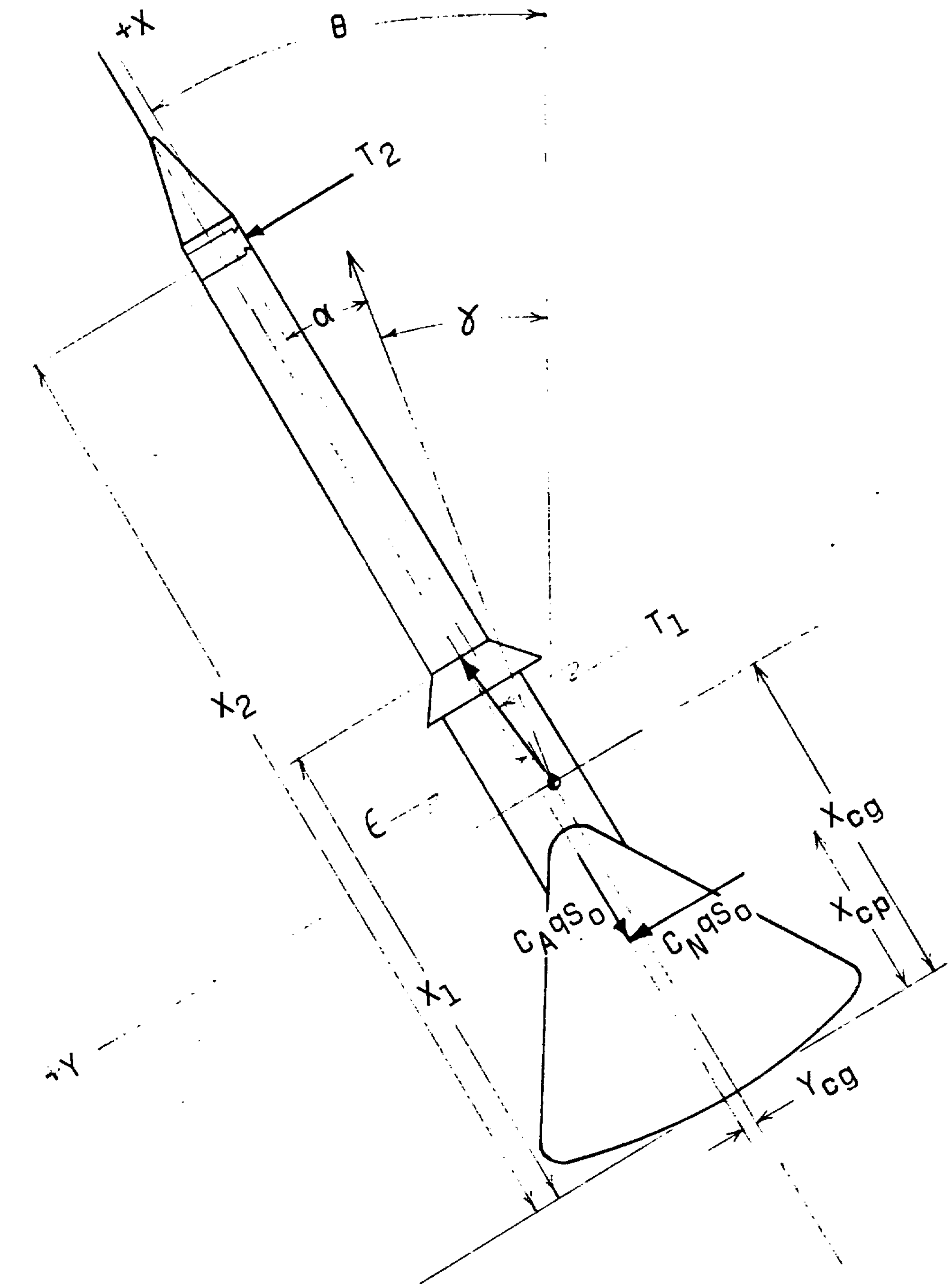

Figure 3.- Launch escape system configuration.

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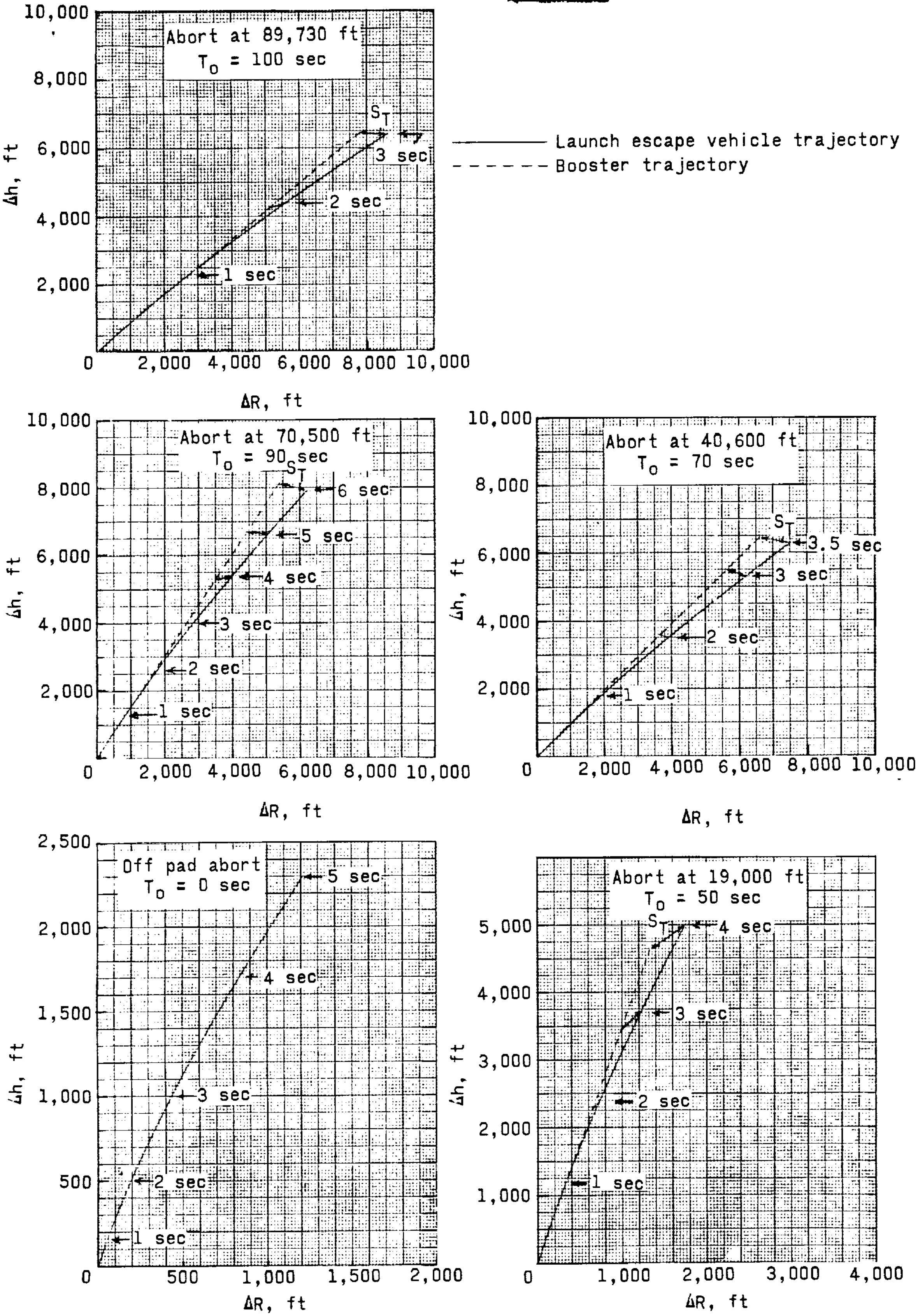

Figure 4.- Post abort trajectories launch escape vehicle and booster.

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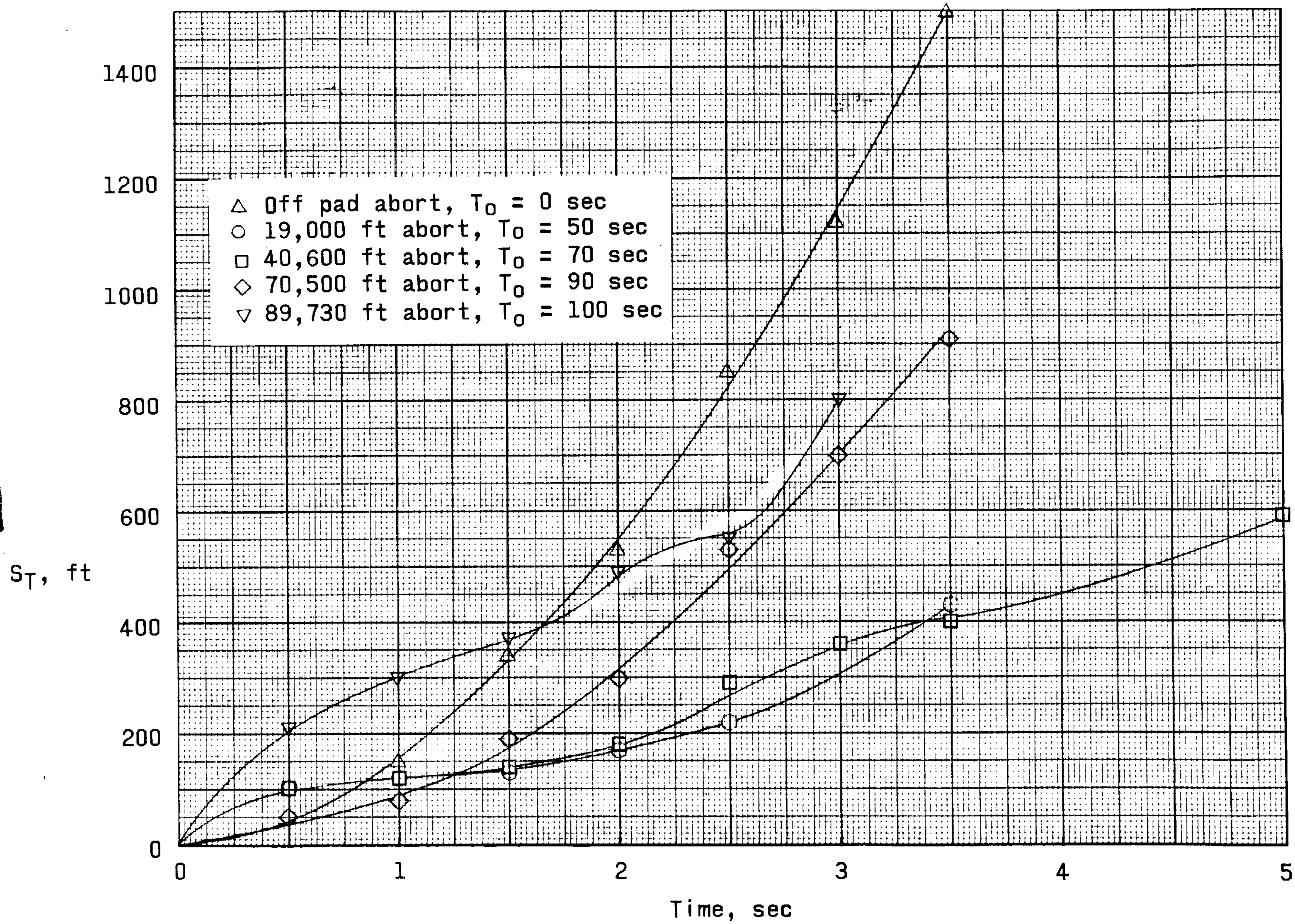

Figure 5.

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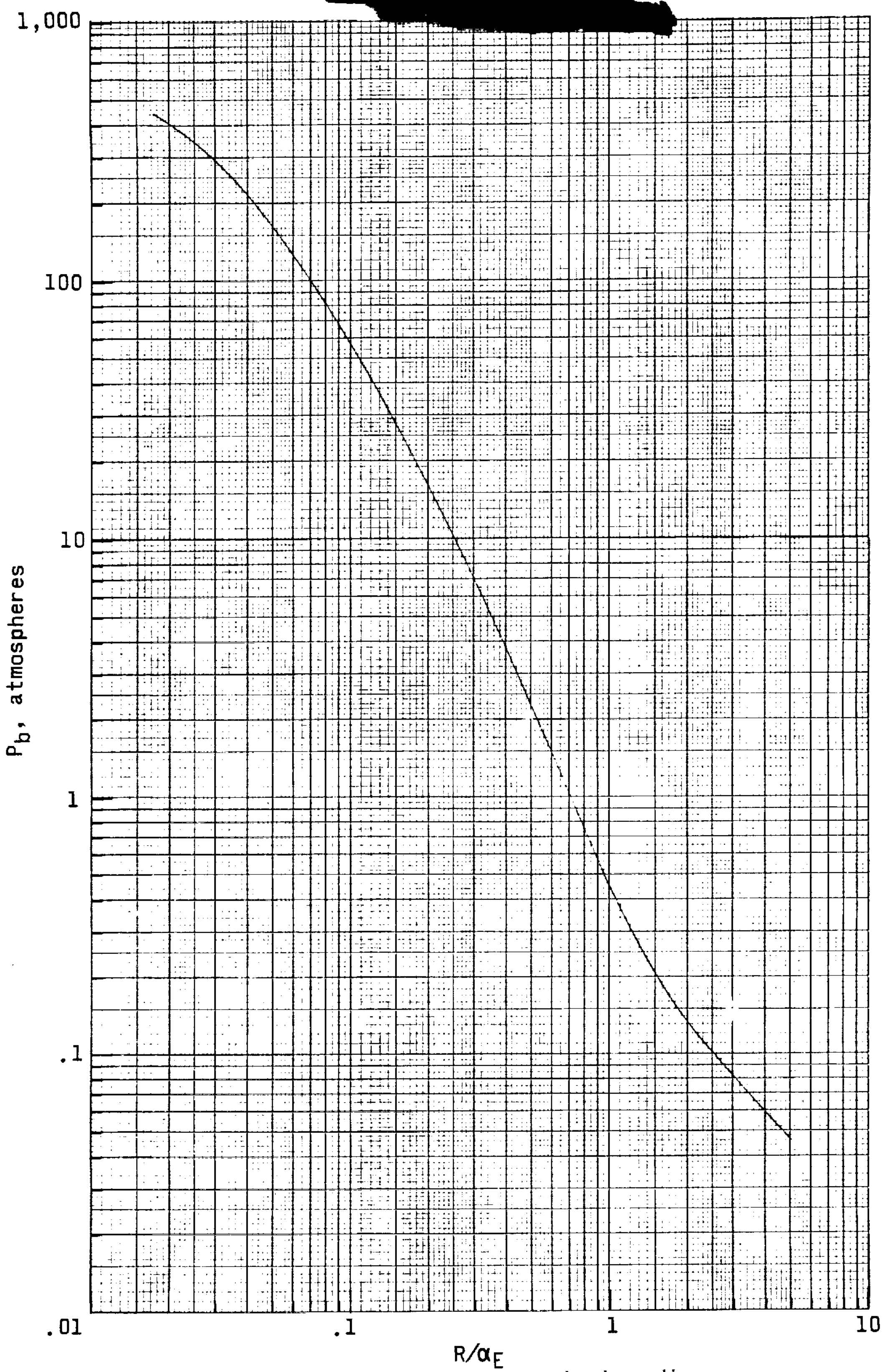

Figure 6.- Peak overpressure versus shock radius.
Note: Atmospheres here correspond to the altitude at which the explosion occurs. (Ref. 5, page 25, Fig. 1)

[redacted]

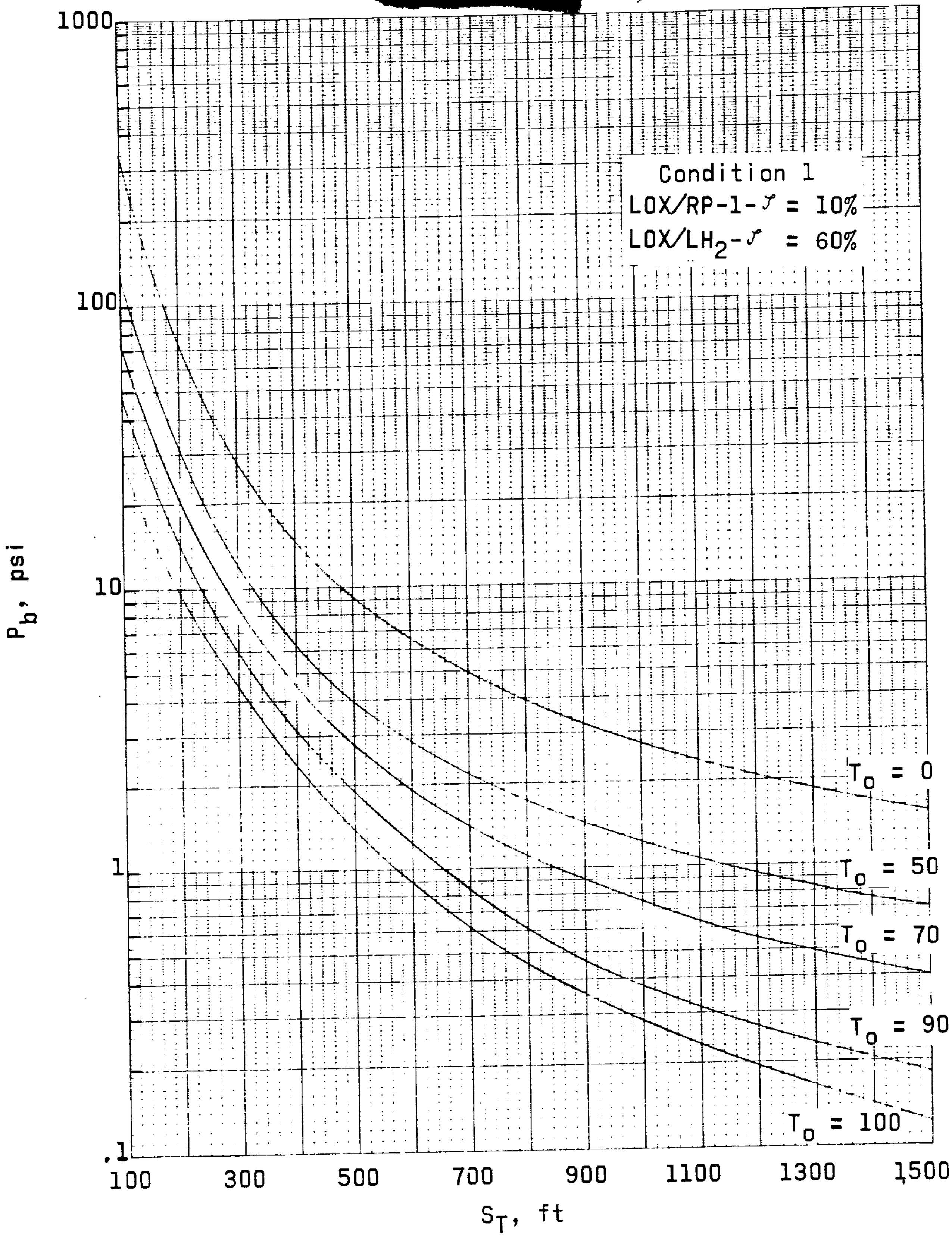

Figure 7.- Blast overpressure versus seperation distance.

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[redacted]

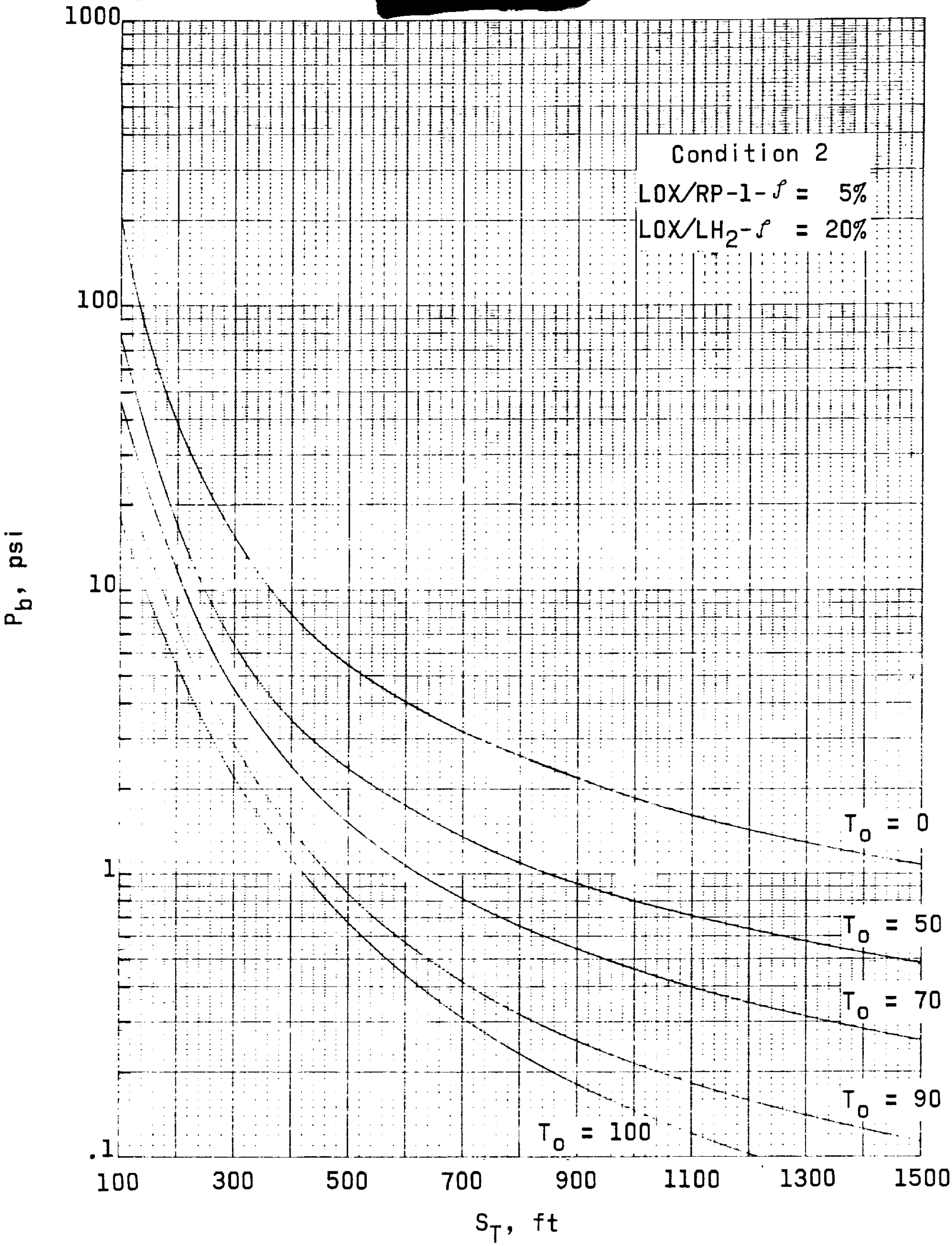

Figure 8.- Blast overpressure versus seperation distance.

[redacted]

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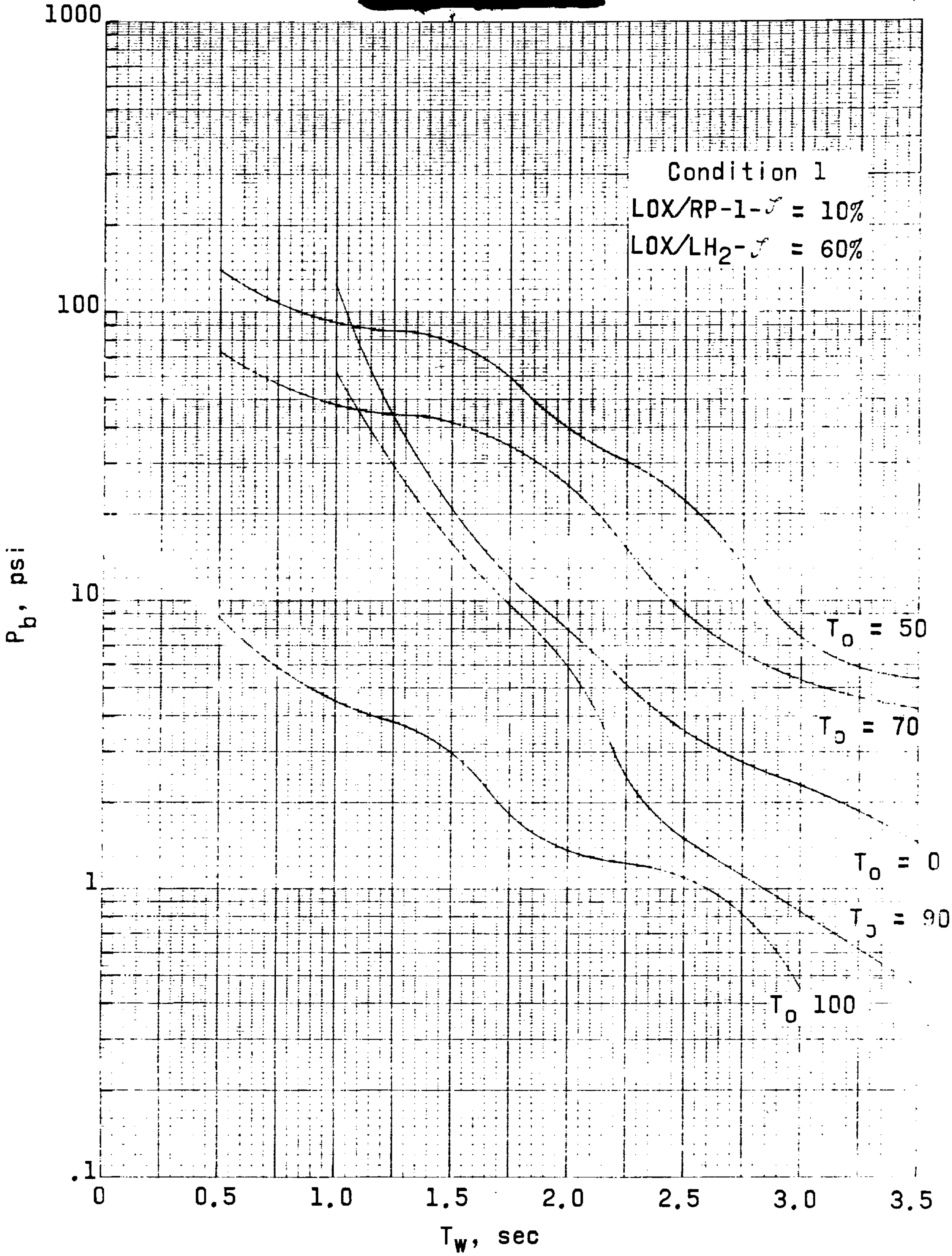

Figure 9.- Overpressure versus warning time.

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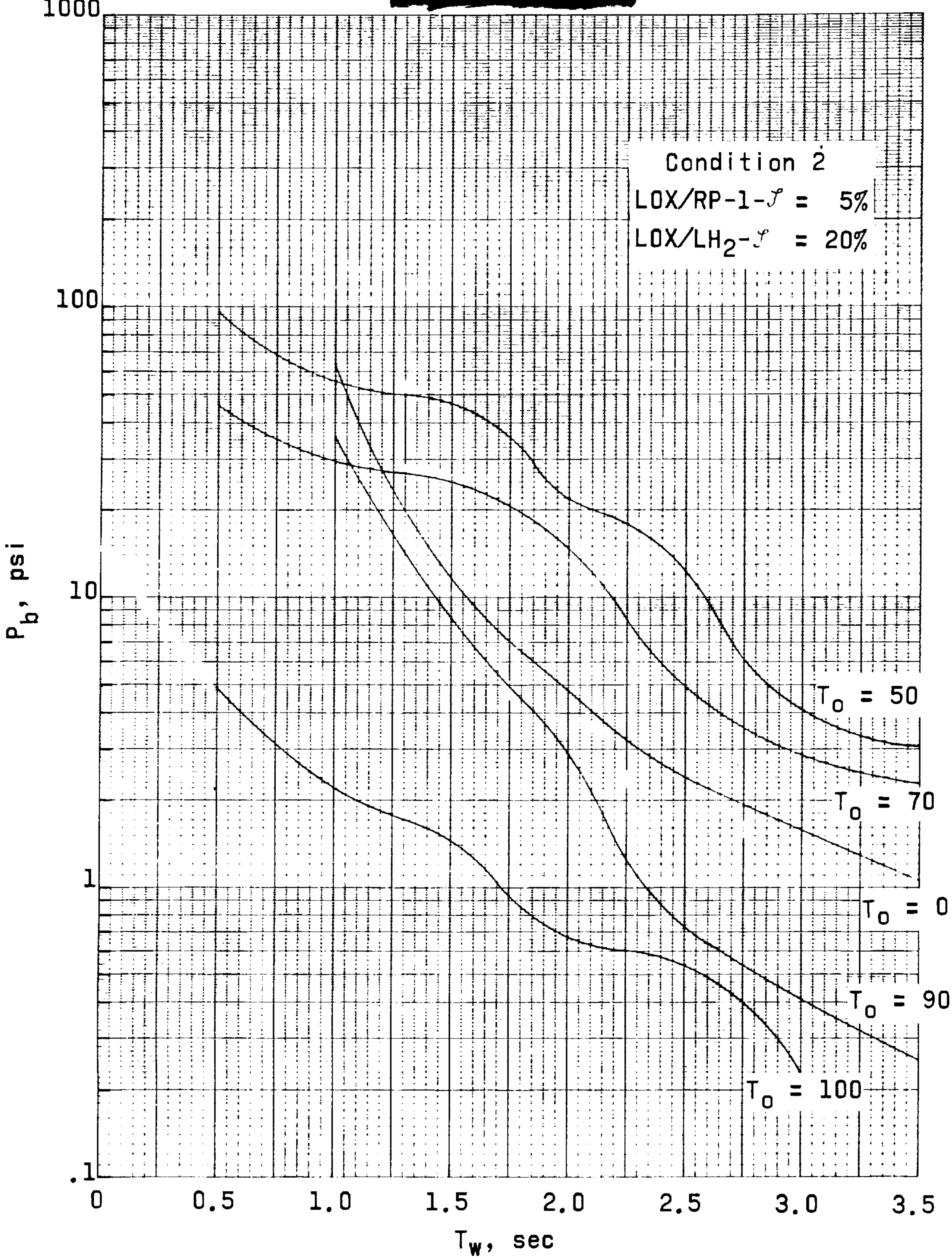
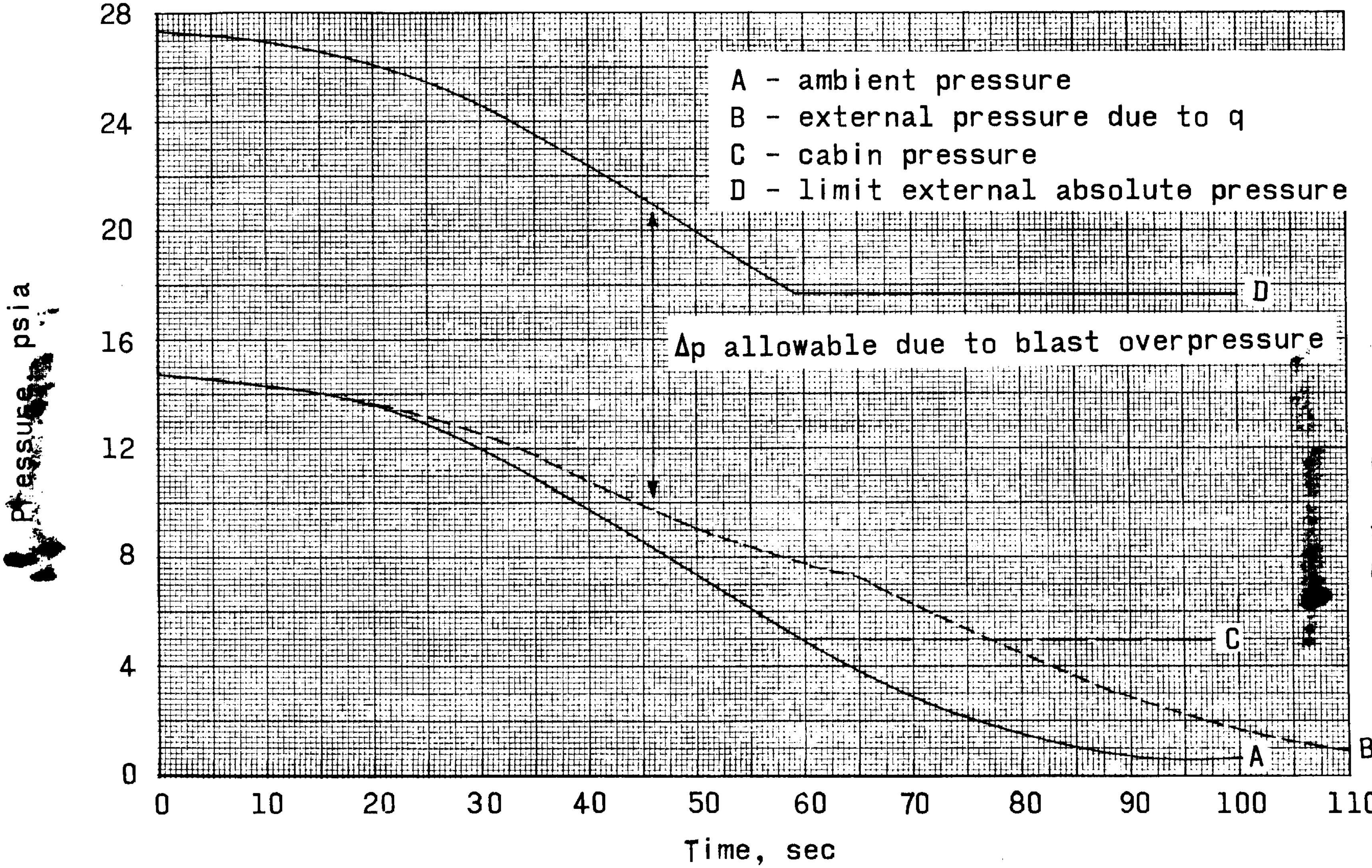


Figure 10.- Overpressure versus warning time.

[redacted]

[redacted]



[redacted]

Figure 11.- Time history of command module pressures.

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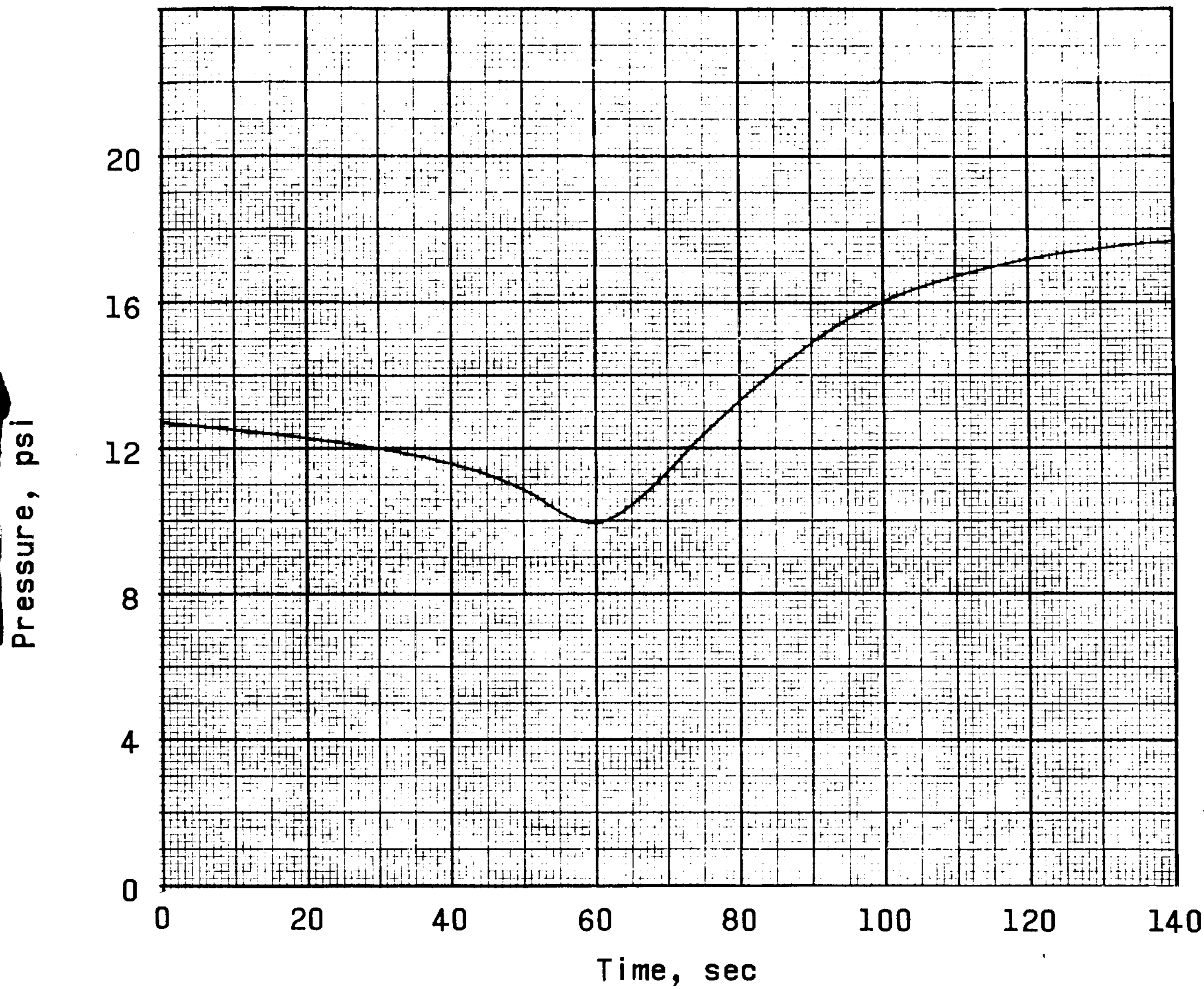

Figure 12 .- Allowable limit blast overpressure.

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